Plasmaspheric Science and the Radiation Belts Storm Probes (RBSP) Mission

1. Plasmaspheric Influence on Radiation Belts

The plasmasphere is the cold (1 eV or less), dense (10-10,000 cm^{-3}) innermost region of the magnetosphere that is populated by upflow of ionospheric plasma along geomagnetic field lines [*Lemaire and Gringauz*, 1998]. During prolonged periods of very quiet geomagnetic conditions (when ionospheric filling is the dominant effect), the plasmasphere can become quite large, reaching beyond geosynchronous orbit (6.62 R_E) and having no distinct outer boundary [*Goldstein and Sandel*, 2005]. However, during geomagnetically active periods the outer layers of the plasmasphere are eroded by enhanced sunward convection that is mainly driven by dayside magnetopause reconnection but significantly modified by strong electric fields that result from ionospheric closure of the partial ring current. Erosion causes the plasmasphere outer boundary, the plasmapause, to move inward on the nightside and outward on the dayside to form plumes of dense plasma extending sunward into the outer magnetosphere. Directly confirming the earliest plasmaspheric models [e.g., *Grebowsky*, 1970], global images obtained by the IMAGE mission demonstrate that plume formation is a consistent plasmaspheric response to enhanced convection, and that on an event-by-event basis plume evolution follows a repeatable and predictable pattern [*Goldstein and Sandel*, 2005]. The global plasmaspheric configuration bears directly on the evolution of the radiation belts because cold plasma can host electromagnetic waves that cause both energization and loss of energetic electrons [*Albert*, 2004]. The following sections will illustrate the profound influence of the plasmasphere upon the radiation belts, and how this influence must be studied to obtain closure of the prioritized science objectives of the Radiation Belt Storm Probes (RBSP) mission.

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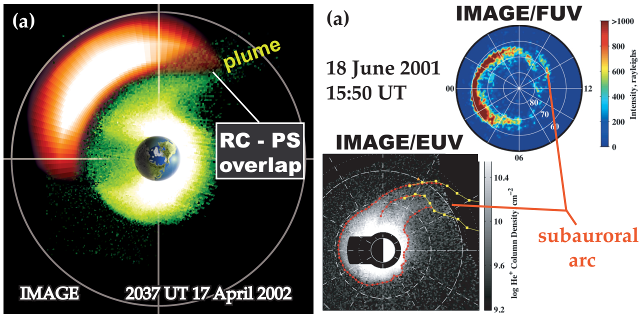


Figure 1. (a) Global composite image of the inner magnetosphere [*Goldstein*, 2005]. Shown is the SM-coordinate magnetic equatorial plane (northern vantage). Sun is to the right, Earth is in the center; geosynchronous orbit (6.6 R_E) and the X- and Y- axes are drawn in. Green region: IMAGE EUV He$^+$ plasmasphere, exhibiting duskside plume. Orange region: IMAGE/HENA proton pressure (10–60 keV, 0.5–0.8 nPa) image has been overlaid onto global plasmasphere snapshot from IMAGE/EUV. The plasmasphere and ring current are roughly spatially complementary, but overlap at the eastern edge of the plasmaspheric plume. (b) Overlap of the ring current and plasmasphere can lead to EMIC waves that can scatter hot particles into the ionosphere, leading to subauroral arcs of precipitation [*Spasojević et al.*, 2005] that map to the eauatorial location of the plume.

1.1. Effects of Cold Plasma

Electromagnetic waves inside the plasmasphere and near the plasmapause can alter both the pitch-angles and the energies of the hot particles [*Kennel and Petschek*, 1966]. First the background and outstanding questions will be described, and then the method of attack.

1.1.1. Wave-Particle Losses.

This subsection discusses pitch-angle scattering by wave-particle interactions in and near the plasmasphere.

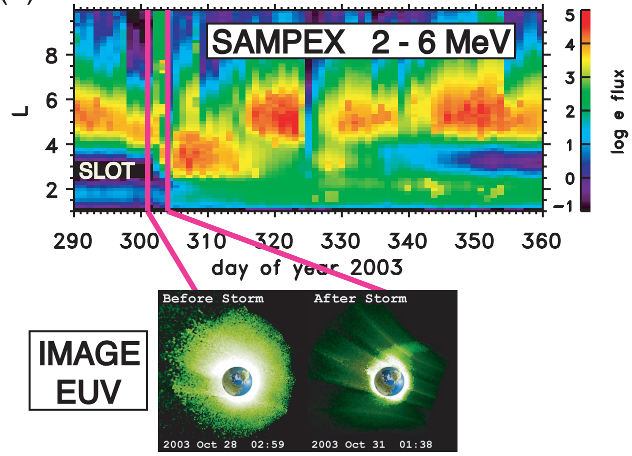
1.1.1.1. Plumes and Flux Dropouts:

The overlap between the ring current and plasmasphere can favor the growth of electromagnetic ion cyclotron (EMIC) waves that can pitch-angle scatter hot particles (both ring current ions and radiation belt electrons). The plasmasphere and ring current are observed to be, on average, roughly spatially complementary [*Daglis et al.*, 1999], but plasmaspheric erosion causes the formation of plumes of plasma that extend outward across the L-shells populated by the ring current (see **Figure 1**a), so that ring current ions encounter the eastern edges of plumes most often in the dusk sector, generating EMIC waves in this region. Observations by DE and CRRES have indeed shown that EMIC waves are more likely to occur on the dusk side and in the vicinity of cold plasma, both in statistical studies [*Erlandson and Ukhorskiy*, 2001; *Fraser and Nguyen*, 2001] and case studies [*Spasojević et al.*, 2005]. Observations attest that EMIC waves are effective at scattering energetic particles [*Lorentzen et al.*, 2000; *Millan et al.*, 2002], and models predict the EMIC-related diffusion coefficients and particle decay rates [*Summers and Thorne*, 2003; *Albert*, 2004], but these models need to be observationally tested and constrained to address RBSP science objectives **(2)**, **(3)**, **(4)**, and **(8)**. EMIC waves are a candidate to explain sharp storm-time electron flux dropouts that can occur in just a few hours [*Onsager et al.*, 2002; *Baker et al.*, 2004], especially considering the consistent presence of broad dayside plasmaspheric plumes during storms, but the importance of EMIC scattering in plumes relative to adiabatic transport must be established. Although at the start of erosion plumes are quite broad in (encompassing much or most of the dayside MLT sector), the plumes become much narrower on a time scale of a few to several hours. The fraction of their drift paths that energetic electrons spend in the plume (the proposed loss region) is inversely proportional to the MLT width of the plume. Therefore, for EMIC-induced losses to play a role in flux dropouts EMIC wave amplitudes and efficiency of the associated pitch-angle scattering must be very high to account for the time scales of the flux dropouts. Specific science questions: (a) What is the quantitative relation between the presence of cold plasma plumes and the global distribution of EMIC wave occurrence and amplitude? (b) What is the quantitative contribution of EMIC pitch-angle scattering to storm-time flux dropouts? (c) Is there a relationship between the rapidity of a particular flux dropout and the initial MLT extent of the plasmaspheric plume?

1.1.1.2. The Plasmasphere and the Slot Region:

Observations throughout the plasmasphere typically reveal the presence of broad-band whistler mode emission known as plasmaspheric hiss [*Thorne et al.*, 1973]. From CRRES data, hiss amplitudes and occurrence rates increase dramatically with geomagnetic activity (e.g., reaching 30–100 pT for large substorms), and are spatially peaked on the dayside [*Meredith et al.*, 2004]. This observational evidence strongly suggests hiss is generated by convective injection of plasma sheet electrons; these injected electrons would drift eastward onto the dayside where they would encounter plasma plumes formed by the same convection responsible for the injection. Observations also indicate a small component of hiss is generated by lightning [e.g., *Green et al.*, 2005], although these amplitudes are orders of magnitude smaller than the dominant, geomagnetically generated component. It has long been suspected that pitch-angle scattering by hiss is the primary formative cause of the slot region [e.g., *Lyons et al.*, 1972], and thus the outer extent of the plasmasphere should be of fundamental importance in predicting the inner extent of the outer belt electrons. *O'Brien and Moldwin* [2003] showed a correlation between the statistical/modeled location of the plasmapause and the outer extent of the slot region. Using observations by IMAGE EUV and SAMPEX together, *Baker et al.* [2004] showed a close relationship between the plasmapause and the outer belt during the dramatic 2003 Halloween storm (see **Figure 2**a), and *Goldstein et al.* [2005b] extended this type of analysis to cover a two-month period (see **Figure 2**b). On time scales of 3.5 days or more, the correspondence between the plasmapause and outer belt holds to within 0.1–0.3 R_E, though particle flux decay rates inferred from SAMPEX data are variable on an event-by-event basis. The plasmasphere-outer belt correspondence strongly indicates a loss term associated with the presence of cold plasma, but theoretical studies of electron lifetimes support the idea that the plasmasphere's role in creating and maintaining the slot region is a combination of both hiss (inside and throughout the plasmasphere) and EMIC wave scattering (near the plasmapause). This topic is of great importance to addressing RBSP science objectives **(2)**, **(3)**, **(4)**, and **(8)**. Specific science questions: (a) What is the quantitative relation between the persistent presence and distribution of cold plasma and the global distribution of hiss wave occurrence and amplitude? (b) What are the quantitative contributions of hiss and EMIC waves to the pitch-angle scattering that creates and maintains the slot region? (c) What role (if any) does hiss-induced scattering play in the dynamics of energetic electrons on storm time scales?

(a) 2003 Halloween Storm



(b) March - May 2001

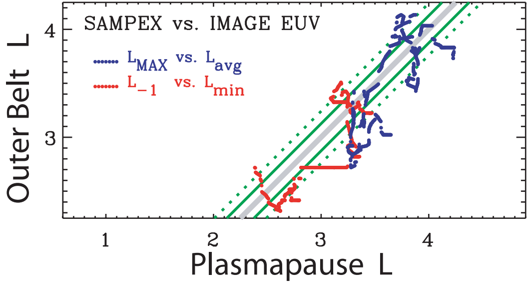


Figure 2. Plasmasphere Control of Radiation Belts. (a) 2003 Halloween Storm [*Baker et al.*, 2004]. SAMPEX observed an extreme inward distortion of the outer belt that completely filled the slot region for almost two weeks, while IMAGE EUV witnessed a severe erosion of the plasmasphere (to below $L = 2$). During this time the inner extent of the outer belt tracked the plasmapause. (b) Two-month study illustrating general correspondence between plasmapause and outer belt [*Goldstein et al.*, 2005b]. The L value of peak electron flux (L_{MAX}) tracks the average plasmapause, and the location of a tenfold flux decrease (L_{-1}) follows the minimum plasmapause. Grey diagonal; perfect agreement. Green diagonal: standard deviation of scatter, $0.1L$. Dotted diagonal: mean deviation of scatter, $0.3L$.

1.1.2. Wave-Particle Acceleration.

This subsection deals with plasmaspheric influence on energization of radiation belt electrons.

1.1.2.1. Chorus near the Plasmapause:

Energy diffusion by chorus (a type of whistler mode radiation) is thought to be a major means of accelerating plasma sheet/ring current electrons to relativistic energies. Statistically, chorus intensifies with convection and is confined on the dawnside outside the average location of the plasmapause [*Meredith et al.*, 2003], arguing for chorus generation by eastward-moving plasma sheet electrons, perhaps encountering the plasmapause (analogous to EMIC wave generation by westward-moving ring current ions inside duskside plumes) [*Kennel and Petschek*, 1966]. Modeling of the time scale for chorus acceleration indicate that a low ratio f_{pe}/f_{ce} enables larger energy diffusion (i.e., more efficient acceleration), meaning that in general [*Horne et al.*, 2005; *Albert*, 2004]. Thus, both the average spatial variation of chorus and the model calculations indicate acceleration of electrons occurs most efficiently in the portion of the inner magnetosphere not occupied by the plasmasphere. The state of the radiation belt depends on a dynamic imbalance of energization and loss terms. Outside and near the plasmapause, acceleration is more efficient; inside and near the plasmapause, losses are more efficient. Given that radiation belt flux build-ups happen during the recovery phase (when cold plasma density gradually increases owing to refilling, and the plasmapause gradually moves outward in L), the spatial dependence of chorus-acceleration efficiency indicates that the creation of a new radiation belt occurs inside a volume of space whose inner edge moves gradually outward during recovery. This topic bears on RBSP science objectives **(1)**, **(3)**, **(4)**, and **(8)**. Science questions: (a) What is the detailed, quantitative relationship between the cold plasma density distribution and the origin and generation of chorus? (b) How do chorus-acceleration and the various loss terms contribute to produce a net energization that creates enhanced outer belt fluxes? (c) How does this "net energization region" evolve in space and time as the recovery phase plasmasphere expands in L?

1.1.2.2. Plasmasphere Influence on ULF Wave Acceleration:

Modeling of major storms using particle-tracing simulations has shown that fast mode and shear Alfvén waves in the ultra-low frequency (ULF) range can effectively accelerate electrons to relativistic energies [*Hudson et al.*, 1997; *Elkington et al.*, 2002, 2003]. However, the quantitative contribution of this energization term, relative to all possible sources of energization and loss, is not yet determined, in part because the global cold plasma distribution has never been sufficiently well characterized (both in terms of number and mass density) to properly estimate the global properties of the ULF waves that must do the accelerating. Although the recent advent of global plasmasphere imaging by IMAGE EUV has begun to address this problem [*Sandel et al.*, 2001; *Adrian et al.*, 2004; *Kim et al.*, 2005], critical questions remain if we are to quantify ULF wave acceleration and obtain closure in RBSP science objectives **(1)**, **(3)**, **(4)**, and **(8)**. Science questions: (1) How do propagating ULF waves interact with the global density distribution to produce the spectral and spatial properties necessary to accelerate electrons to relativistic energies? (2) Can ULF waves become partially confined inside the plasmasphere, or part of the plasmasphere (e.g., the plume) to create resonances that play a role in energization? (3) Which wave modes more efficiently energize particles: fast mode (cross-L propagating) or shear mode (propagating along field lines)? (4) Which is more effective at accelerating electrons: narrow-band (resonant) or broad-band ULF energy?

1.2. Methodology

Investigation of these questions will require a coordinated approach using both observations and modeling. Observations required are: the cold plasma density (both number density and composition), wave amplitudes, fluxes and pitch-angles of energetic electrons. Electric field measurements will strongly support the plasmaspheric modeling effort. Global modeling of the plasmasphere, and calculations of EMIC, hiss, and chorus wave growth rates and energy and pitch-angle diffusion coefficients must be performed. *This document will only discuss the observation and modeling of the plasmasphere. It will be assumed that the model calculations (wave growth rates, diffusion coefficients, electron fluxes) that rely on knowledge of the cold plasma are described in other sections of the compiled proposal.* In this regard, our requirements are as follows. To study losses from hiss and EMIC waves, we need to know where the plasmapause is, and what the global mass density is inside the plasmapause. To study chorus acceleration, we need to know where the plasmasphere is not. To comprehensively model ULF acceleration, we need the global distribution of density inside and outside the plasmasphere, but the most important consideration is the global mass density inside the plasmapause, for the following reasons. It is at the steep plasmapause gradient (where the mass density can change by two to three orders of magnitude in less than 1 R_{E}) that the strongest fast-mode/shear-mode coupling occurs, creating the most intense field line resonances (FLRs). The plasmapause also defines the steepest reflector for fast mode waves that is inside the magnetopause, and so is of critical importance in quantitatively characterizing the propagation of ULF waves throughout the inner magnetosphere where radiation belt electrons are energized.

Recent improvements in plasmasphere models [e.g., *Goldstein and Sandel*, 2005; *Goldstein et al.*, 2005c, a] indicate that given some key information, the global inner magnetospheric convection field can be modeled sufficiently well to reproduce the observed global plasmapause location to within 0.2–0.7 R_{E}. For radiation belt physics, this level of accuracy is sufficient because finer-scale structure is not likely to play a role in the dynamics of rapidly drifting energetic electrons. It is the integrated effect of the dynamically evolving plasmasphere, over the course of the time necessary for various energization and loss processes to occur, that is important for RBSP, and with confidence it can be said that this is achievable with our current level of modeling sophistication. This confidence stems in part from the fact that global images have allowed us to validate our models.

The information necessary for a successful storm-time plasmapause modeling effort for RBSP is (A) solar wind and IMF measurements (for magnetospheric input and determination of when dayside reconnection is occurring); (B) some knowledge of the ratio of the strength of the E-field near the plasmapause (to be measured in situ) to the solar wind E-field; and (C) a rough (to within 1 R_{E} at some MLT) knowledge of the initial state of the plasmasphere before each storm. The first quantity will be provided by ACE data, the second by RBSP's in situ E-field instrument. Estimating the third quantity presents a problem that is surmountable because of the particular behavior of the storm-time plasmasphere. While decades of observations show that it can be dificult to infer the global plasmapause based solely on single-point measurements, during major storms most of the initial information is wiped out by dramatic erosion, so that it is only necessary to get the approximate initial global configuration. After several hours of strong erosion, the plasmapause shape is determined primarily by the integrated effect of the time history of the dynamic convection E-field. Successful plasmapause modeling has a side-benefit. Because the cold plasma responds almost exclusively to $E \times B$ drift, knowledge of the plasmapause provides an indicator of the global inner magnetospheric electric field (necessary for proper modeling of the ring current "seed" population), and of the general history and present geomagnetic state of the magnetosphere.

2. Measurement Requirements for Plasmaspheric Science

Listed in a separate document.

3. RBSP Science Objectives

The RBSP prime science objective: *Understand the acceleration, global distribution, and variability of energetic electrons and ions in the inner magnetosphere.* This prime objective breaks down into several prioritized specific objectives. The following subset are those objectives that are addressed by plasmaspheric influence (as described above):

(1) differentiating among competing processes affecting the acceleration and transport of radiation particles;

(2) differentiating among competing processes affecting the precipitation and loss of radiation particles;

(3) understanding the creation and decay of new radiation belts;

(4) quantifying the relative contribution of adiabatic and nonadiabatic processes on energetic particles;

(5) developing and validating specification models of the radiation belts for solar cycle time scales.

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